CS429: Computer Organization and Architecture

Introduction

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Abstraction is our Friend

Most of what we study in Computer Science is really about a hierarchy of abstractions!

- Theme of the course
- Great realities of computer science
- How this class fits into the CS curriculum
Abstraction vs. Reality

**Abstraction is good, but don’t forget reality!**

Most of your courses to date have emphasized abstraction.
- High level programming languages
- Abstract data types
- Asymptotic analysis

These abstractions have limits!
- Especially in the presence of bugs
- Need to understand underlying implementations
- Need to have a working understanding of architecture

**Useful outcomes!**
- Know “stuff” that all computer scientists should know
- Become more effective programmers
  - Able to find and eliminate bugs efficiently
  - Able to tune program performance
- Prepare for later “systems” classes: Compilers, Operating Systems, Networks, Computer Architecture, Embedded Systems, many others.

**Hint:** Hang onto your book. You’ll be using this same book (3rd edition) in CS439.

Great Reality 1

**Ints are not Integers; Floats are not Reals.**

Is \( x^2 \geq 0? \) For floats, yes. For ints, not necessarily.

\[
\begin{align*}
40000 \times 40000 & \rightarrow 1600000000 \\
50000 \times 50000 & \rightarrow??
\end{align*}
\]

Floats are not Reals

- Sign: 0 => positive
- Exponent:
  - 0110 1000 101010 0100 0011 0100 0010
  - Bias adjustment: 10 + 127 = 137
- Significant:
  - \( 1 + 1 \times 2^{-1} + 2^{-3} + 2^{-4} + 1 \times 2^{-6} +... = 1 + 2^{-1} + 2^{-3} + 2^{-4} + 2^{-14} + 2^{-16} + 2^{-17} + 2^{-22} \)
  - \( 1.0 + 0.666115 \)
- Represents: 1.666115*2^{-2} \approx 1.986*10^{-7}

Is \((x + y) + z = x + (y + z)\)? For int’s: yes. For floats, maybe not.

- \((1e20 + -1e20) + 3.14 \rightarrow 3.14\)
- \(1e20 + (-1e20 + 3.14) \rightarrow??\)
Treat CS as an Experimental Science

Get into the habit of writing programs to experiment with the architecture:

```c
void main()
{
    printf("40000 * 40000 = %d\n", 40000 * 40000);
    printf("50000 * 50000 = %d\n", 50000 * 50000);
    printf("1e20 + (−1e20 + 3.14) = %f\n", 1e20 + (−1e20 + 3.14));
    printf("(1e20 + −1e20) + 3.14 = %f\n", (1e20 + −1e20) + 3.14);
}
```

> gcc tester.c
> a.out

40000 * 40000 = 1600000000
50000 * 50000 = −1794967296
1e20 + (−1e20 + 3.14) = 0.000000
(1e20 + −1e20) + 3.14 = 3.140000

Computer Arithmetics

Computer arithmetic does not generate random values. Arithmetic operations have important mathematical properties.

But not the “usual” properties of arithmetic.
- Due to finiteness of representations.
- Integer operations satisfy ring properties: commutativity, associativity, distributivity.
- Floating point operations satisfy ordering properties: monotonicity, values of signs.

Observation:
- Need to understand which abstractions apply in which contexts.
- Important issues for compiler writers and serious application programmers.

Great Reality 2

**Computer scientists should understand assembly language!**

You won’t often program in assembly. Compilers are much better at it and more patient than you are.

Understanding assembly is key to understanding what really happens on the machine.
- Behavior of programs in presence of bugs; high-level language model breaks down.
- Tuning program performance and understanding sources of program inefficiency.
- Implementing system software
  - Compiler has machine code as target
  - Operating systems must manage process state
- Creating / fighting malware: x86 is the language of choice for attackers.

Great Reality 3

**Memory Matters!**

Memory is not unbounded!
- It must be allocated and managed.
- Many applications are memory dominated.

Memory referencing bugs are especially pernicious. The effects may be distant in both time and space.

Memory performance is not uniform.
- Cache and virtual memory effects can greatly affect program performance.
- Adapting your programs to characteristics of memory system can lead to major speed improvements.
**Memory Referencing Bug Example**

```c
double fun(int i)
{
    int a[2];
    double d[1] = {3.14};
    a[i] = 1073741824;
    return d[0];
}
```

Assume x86 (double is 8 bytes; int is 4 bytes). This will be different on other systems, and may cause segmentation fault on some.

<table>
<thead>
<tr>
<th>Call</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>fun(0)</td>
<td>$\rightarrow 3.14$</td>
</tr>
<tr>
<td>fun(1)</td>
<td>$\rightarrow 3.14$</td>
</tr>
<tr>
<td>fun(2)</td>
<td>$\rightarrow 3.1399998664856$</td>
</tr>
<tr>
<td>fun(3)</td>
<td>$\rightarrow 2.00000061035156$</td>
</tr>
<tr>
<td>fun(4)</td>
<td>$\rightarrow 3.14, \text{ then segmentation fault}$</td>
</tr>
</tbody>
</table>

What can you infer about how the memory is laid out?

**Memory Referencing Errors**

C and C++ do not provide much memory protection.
- Out of bounds array references
- Invalid pointer values
- Abuses of malloc/free

This can lead to nasty bugs.
- Whether or not bug has any effect depends on system and compiler.
- Action at a distance
  - Corrupted object logically unrelated to one being accessed.
  - Effect of bug may be first observed long after it is generated.

How can I deal with this?
- Program in Java, Lisp, or ML
- Understand what possible interactions may occur
- Use or develop tools to detect referencing errors

**Memory Performance Example**

The following copies an $n \times n$ matrix:

```c
/* ij */
for (i=0; i<n; i++) {
    for (j=0; j<n; j++) {
        b[i][j] = a[i][j];
    }
}
```

This one computes precisely the same result.

```c
/* ji */
for (j=0; j<n; j++) {
    for (i=0; i<n; i++) {
        b[i][j] = a[i][j];
    }
}
```

But the performance may be much (could be 10X) slower, particularly for large arrays. Can you guess why that may be?
Great Reality 4

There’s more to performance than asymptotic complexity.

**Constant factors matter too!**
- Even an exact op count does not predict performance.
- Easily see 10:1 performance range depending on how code is written.
- Must optimize at multiple levels: algorithm, data representations, procedures, and loops.

**Must understand the system to optimize performance.**
- How programs are compiled and executed.
- How to measure program performance and identify bottlenecks.
- How to improve performance without destroying code modularity and generality.

Great Reality 5

Computers do more than execute programs.

They need to get data in and out. The I/O system is critical to program reliability and performance.

**They communicate with each other over networks.** Many system-level issues arise in the presence of networking.
- Concurrent operations by autonomous processes
- Coping with unreliable media
- Cross platform compatibility
- Complex performance issues

Great Reality 6 (I Added this One)

Computers do a lot with very simple primitives.

Nobel Prize winner (in Economics) Herbert Simon used an ant to explain how simple actions can explain complex results. *(Sciences of the Artificial, 1969)*

Imagine an ant walking along a beach. You notice that the ant is tracing a very intricate path. **Must be executing a pretty complex algorithm, right?**

Lesson: You can generate very complex results using only very simple tools.

Simon's Ant
A **Turing Machine** is a very simple computing device that can look at a symbol on a tape, write another symbol, and move right or left one square, under the direction of a simple program.

**Everything that can be computed can be computed by a Turing Machine.**

The most powerful computer you’ll ever use in your life is **no more powerful than a Turing Machine**. We say that a machine is **Turing complete** if it can emulate a Turing machine.

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**Course Perspective**

**Most systems courses are “builder-centric.”**

- Computer Architecture: Design pipelined processor in Verilog.
- Operating Systems: Implement large portions of operating system.
- Compilers: Write compiler for simple language.
- Networking: Implement and simulate network protocols.

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**Our Subject: Computer Organization**

**This course is programmer-centric.**

- The purpose is to show how by knowing more about the design of the underlying system, one can be more effective as a programmer.
- Enable you to
  - Write programs that are more reliable and efficient
  - Incorporate features that require hooks into OS: concurrency, signal handlers, etc.
- Not just a course for dedicated hackers. We bring out the hidden hacker in everyone.
- Cover material in this course that you won’t see elsewhere.